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# Tunable Duplexers: Downlink Band Isolation Requirements for LTE User Equipment

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**Abstract**—Tunable duplexers based on self-interference cancellation present a promising alternative to fixed-frequency duplexers (e.g. surface acoustic wave devices), however the level of transmit-to-receive (Tx-Rx) isolation they provide is typically lower compared to acoustic devices. This paper quantifies the impact of reduced isolation on receiver (Rx) noise figure (NF), and determines minimum isolation requirements for Tx-Rx isolation in cellular handset transceivers. Measurements of Tx noise power spectral density from a cellular handset power amplifier are combined with theoretical analysis and long term evolution (LTE) downlink throughput simulations to assess the impact of isolation on the noise figure and sensitivity. Although lower duplexer isolation can lead to substantial desensitization for some duplex separation/bandwidth combinations, achieving LTE compliant sensitivity requires only 38 dB of isolation in the Rx band. LTE sensitivity specification compliance is therefore readily achievable with current tunable duplexing technologies.

**Index Terms**—Full duplex, duplexers, electrical balance duplexer, frequency division duplex, self-interference cancellation, LTE, noise.

## I. INTRODUCTION

**R**ADIO frequency front-end (RFFE) architectures in cellular handsets currently achieve multiband operation through the duplication of transceiver subsystems, requiring multiple transmitters (Tx), receivers (Rx), power amplifiers (PAs), and duplexers, in order to cover the required frequency ranges. For multi-band frequency division duplexing (FDD), multiple off-chip surface acoustic wave (SAW) duplexers are required, with radio frequency (RF) switches used for band selection. The resultant cost and size of the duplexing hardware has motivated substantial recent work research into tunable duplexing technologies [1]–[4].

In FDD systems, duplexers are required to isolate the receiver from the transmitter. Fig. 1 depicts the Tx and Rx spectra in a frequency division duplexing RF front-end. In the uplink band, the high powered Tx signal must be suppressed to within the linear dynamic range (i.e. below the maximum Rx input power) of the receiver to prevent saturation. In the downlink band, the out of band Tx emissions must be suppressed below the Rx noise floor in order to prevent substantial receiver desensitization. An often-quoted figure of

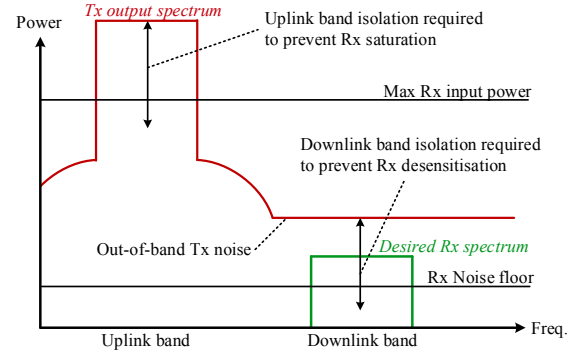


Fig. 1. Typical Tx and Rx spectra in FDD RF front-ends.

merit is that 50 dB of transmit-to-receive (Tx-Rx) isolation is required simultaneously in both the uplink band *and* downlink bands in order to prevent this saturation and desensitization. However, the SAW devices used in commercial LTE user equipment (UEs) often exceed this by a substantial margin; state-of-the-art acoustic resonator duplexers can provide 60–70 dB of isolation [5].

Electrical balance duplexers (EBDs) implement a form of feedforward RF self-interference cancellation based on the balancing of signals within a hybrid junction, and have received substantial interest as a potential alternative to SAW duplexers [1], [2], [4]. EBDs can be implemented within the radio frequency integrated circuit (RFIC), can be tuned over wide frequency ranges [1]. However, the isolation bandwidth of the EBD is limited, and typically cannot provide sufficient isolation simultaneously in the uplink and downlink bands [2]. To address this shortcoming, recent works have investigated combining EBDs with further filtering or cancellation subsystems. In [2] and [3], the EBD is used to provide isolation the downlink band, and is combined with tunable filtering in the Rx path for Tx blocker rejection (see Fig. 2a). Active RF cancellation uses an additional Tx chain to generate a cancellation signal, which is coupled into the receive path to cancel Tx leakage. In [4], an EBD, operating in the downlink band, is combined with an active RF canceler used for Tx blocker suppression in the uplink band (see Fig. 2b). Both of these architectures use the EBD to cancel the Tx noise in the Rx band, and therefore the Tx-Rx isolation achieved by the EBD is a critical factor determining the Rx noise figure (NF). It is notable that the Tx-Rx isolation which can be achieved using an EBD may be substantially lower than that provided by a SAW duplexer. For a 20 MHz bandwidth the isolation may only be 40–55 dB.

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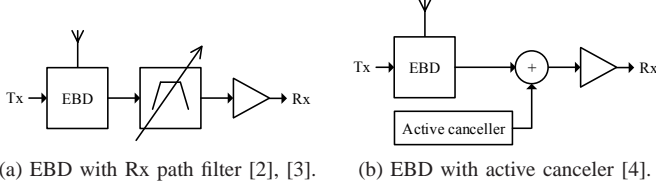


Fig. 2. Two tunable duplexing architectures which utilize an EBD to cancel Tx noise in the Rx band, and combine this with Tx blocker filtering/cancellation.

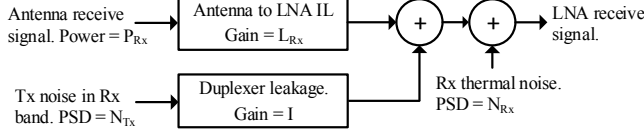


Fig. 3. Downlink band signal model with thermal noise and desensitization.

This paper challenges the assumption that 50 dB of isolation is required to prevent receiver desensitization, and provides quantitative analysis of the impact of Tx-Rx isolation in the downlink band on receiver noise figure, and the resulting effect on downlink throughput for typical LTE UEs. Although the 50 dB isolation threshold is widely used as a pass/fail criterion to determine whether a duplexer meets the requirements of cellular handset applications, our results show that that this is not necessarily an appropriate specification, and minimum isolation required for LTE specification compliance is far lower than this. Desensitization in cellular FDD transceivers has previously been analyzed in [6], which provides a model of non-linearity induced receiver desensitization, and a method for digital cancellation of non-linear self-interference in the receive band. This work differs by characterizing the PA spectral regrowth empirically by measuring the out-of-band noise generated by a handset PA, rather than using non-linear modeling. From this, the impact on Rx sensitivity can be determined using a simple linear signal model. This work deals only with downlink band isolation, assuming that adequate Tx-band suppression is achieved in order to prevent adverse effects due to the Tx blocker (e.g. using filtering or cancellation [3], [4]), and thus a linear Rx can also be assumed. In the following, Section II provides downlink band system noise calculations, developing expressions for the Rx NF as a function of the Tx-Rx isolation and Tx noise. Section III describes hardware measurements from an LTE handset power amplifier (PA), characterizing the Tx noise for different uplink bandwidths and duplex separations, and combining this with the theoretical analysis to determine practical isolation requirements for LTE user equipment (UE) devices. Section IV presents LTE downlink throughput simulations, determining the throughput as a function of Tx-Rx isolation, and establishes the minimum isolation for LTE sensitivity specification compliance. Section V concludes this paper.

## II. DOWNLINK BAND SYSTEM NOISE CALCULATIONS

From the definition of the noise factor, the receiver noise factor,  $F_{Rx}$ , can be written as

$$F_{Rx} = \frac{N_{Rx}}{kT} \quad (1)$$

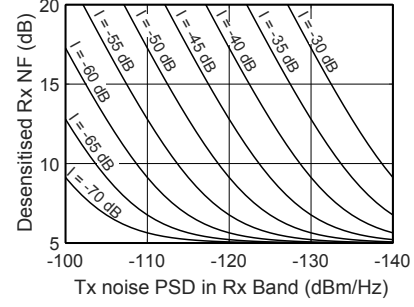


Fig. 4. Calculated noise figure of desensitized receiver as a function of Tx noise PSD for different values Tx-Rx isolation between 30 dB and 70 dB.

where  $N_{Rx}$  is the receiver noise power spectral density (PSD),  $k$  is the Boltzmann constant and  $T$  is the input thermal noise temperature in degrees Kelvin (e.g. 290 K). Assuming the Tx noise and the Tx-Rx isolation are frequency invariant, the PSD of the desensitizing noise due to Tx leakage,  $N_{TxL}$ , can be calculated as

$$N_{TxL} = I N_{Tx} \text{ W Hz}^{-1} \quad (2)$$

where  $N_{Tx}$  is the PSD of the Tx noise in the Rx band, and  $I$  is the Tx-Rx gain (i.e. the leakage channel through the EBD). The noise due to Tx leakage adds to the thermal noise at the receiver (see Fig. 3), and thus the total noise power spectral density of the desensitized receiver,  $N_{RxD}$  is given by

$$N_{RxD} = N_{Rx} + N_{TxL} = N_{Rx} + I N_{Tx} \text{ W Hz}^{-1}. \quad (3)$$

From (1), the noise factor of the desensitized receiver,  $F_{RxD}$ , can therefore be expressed as

$$F_{RxD} = \frac{N_{RxD}}{kT} = \frac{N_{Rx} + I N_{Tx}}{kT} \quad (4)$$

and the noise figure of the desensitized receiver at the LNA input,  $NF_{RxD}$ , is therefore

$$\begin{aligned} NF_{RxD} &= 10 \log_{10}(F_{RxD}) = 10 \log_{10}\left(\frac{N_{Rx} + I N_{Tx}}{kT}\right) \text{ dB} \\ &= 10 \log_{10}(N_{Rx} + I N_{Tx}) - 10 \log_{10}(kT) \text{ dB} \\ &= 10 \log_{10}(N_{Rx} + I N_{Tx}) + 204 \text{ dB} \end{aligned} \quad (5)$$

where  $N_{Rx}$  and  $N_{Tx}$  are expressed in  $\text{W Hz}^{-1}$  and the temperature is taken to be 290 K. To calculate the desensitized Rx NF referred to the antenna port,  $NF_{AntD}$ , the antenna-to-LNA insertion loss must be added to this, such that

$$NF_{AntD} = 10 \log_{10}(N_{Rx} + I N_{Tx}) + 204 + L_{RxdB} \text{ dB} \quad (6)$$

where  $L_{RxdB}$  is the antenna-to-LNA insertion loss in dB, calculated as  $L_{RxdB} = -10 \log_{10}(L_{Rx})$ , where  $L_{Rx}$  is the antenna-to-LNA gain. The insertion loss of the filter (Fig. 2a), or directional coupler (Fig. 2b), add to the Rx insertion loss and Tx-Rx isolation. With reference to the model, this reduces  $L_{Rx}$  and  $I$ . Furthermore, this model assumes that the active canceler employs sufficient filtering to avoid desensitization due to active cancellation (see [4]).

To determine the impact of the Tx leakage on the receiver noise figure, the desensitized antenna referred NF has been evaluated for Tx-Rx isolation values of 30-70 dB, Tx noise

PSD values of  $-100 \text{ dBm Hz}^{-1}$  to  $-140 \text{ dBm Hz}^{-1}$ , and assuming an LNA NF of 2 dB and an Rx IL of 3 dB, which gives an antenna referred NF of 5 dB prior to desensitization. Fig. 4 plots the antenna referred desensitized noise figure,  $NF_{AntD}$ , as a function of Tx noise PSD for a range of isolation values [calculated using (6)]. These results quantify the substantial desensitization that occurs for higher Tx noise PSDs, showing that, as would be expected, much higher levels of isolation, e.g. 60-70 dB, are required to maintain an acceptable Rx NF when the Tx noise is higher. It is clear that duplexers with lower isolation may lead to substantial desensitization, however this depends heavily upon the level of Tx noise in the Rx band. Tx noise PSDs for LTE UE devices are quantified in the following section.

### III. IMPACT OF TX NOISE AND ISOLATION IN LTE UES

To characterize Tx noise in LTE UEs, measurements were performed on a commercial LTE UE PA driven with an LTE uplink signal. The experimental setup is depicted in Fig. 5. A National Instruments USRP-2942R is used to generate the Tx signal, which is then filtered and fed to the PA. The filter is required as the Tx noise floor of the USRP is substantially higher than the Tx noise PSD at the Tx output of a typical UE radio frequency integrated circuit (RFIC). The filter used is a 3<sup>rd</sup> order tunable microstrip interdigital filter. A 10 dB attenuator is included between the USRP and the filter to mitigate the relatively poor output impedance matching of the USRP. The PA used is an RFMD RF7917 LTE UE PA designed for LTE band 28 (700 MHz), operated at its maximum output power of 27 dBm (worst case scenario). This is higher than the specified LTE maximum Tx power to account for Tx insertion losses (which could be higher in a tunable architecture), and will also increase out-of-band Tx noise. A 30 dB attenuator is included at the output of the PA in order to sink Tx power and protect the measurement chain. The Tx noise PSD is measured using a National Instruments PXIe-5644R vector signal transceiver running in spectrum analyzer mode. Due to the limited dynamic range of this instrument, in order to accurately measure the Tx noise, the in-band Tx signal must be attenuated. To this end, a SAW filter is used to pass the noise in the Rx frequency range, and attenuate the uplink signal in the Tx band. The SAW filter used in the Rx path was the Rx filter of a TDK B8538 LTE band 28 duplexer, which has a passband of 758-788 MHz. Appropriate calibrations were applied to account for the loss of the attenuator and filter. The uplink signal used was an single carrier frequency division multiple access (SC-FDMA) signal with quadrature phase shift keying (QPSK) modulation, and uplink bandwidths of 5 MHz, 10 MHz, and 20 MHz were tested. The receive frequency was fixed at 768 MHz, and the duplex separation was varied by changing the Tx carrier frequency ( $f_{Tx}$ ). Three duplex separations were tested: a wide separation, 120 MHz ( $f_{Tx} = 648 \text{ MHz}$ ), a narrow separation, 55 MHz ( $f_{Tx} = 713 \text{ MHz}$ ), and an ultra-narrow separation of 20 MHz (5 MHz uplink bandwidth), as may occur in some carrier aggregation scenarios.

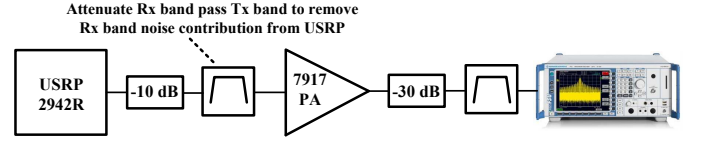


Fig. 5. Hardware setup for measuring Tx noise in the Rx band.

TABLE I  
MEASURED TX NOISE PSD AT RX FREQUENCY AT PA OUTPUT FOR DIFFERENT UPLINK TX BANDWIDTHS AND DUPLEX SEPARATIONS.

Duplex sep.	Uplink BW	Rx noise PSD
120 MHz	5 MHz	-132.4 dBm $\text{Hz}^{-1}$
	10 MHz	-132.5 dBm $\text{Hz}^{-1}$
	20 MHz	-132.1 dBm $\text{Hz}^{-1}$
55 MHz	5 MHz	-131.2 dBm $\text{Hz}^{-1}$
	10 MHz	-124.4 dBm $\text{Hz}^{-1}$
	20 MHz	-107.9 dBm $\text{Hz}^{-1}$
20 MHz	5 MHz	-109.5 dBm $\text{Hz}^{-1}$

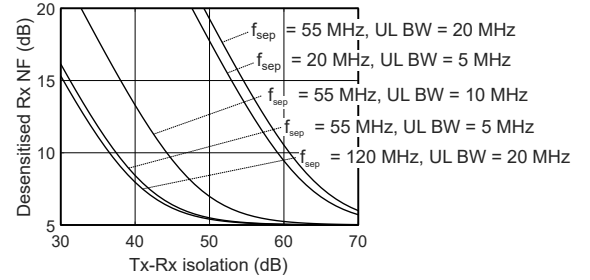


Fig. 6. Calculated desensitized antenna referred NF vs. isolation using measured Tx noise PSD for various duplex separations and uplink BWs.

#### A. Measurement results

The measured PSD of the Tx noise at the Rx carrier frequency are shown in Table I. At the wide duplex separation, the Tx noise is around  $-132 \text{ dBm Hz}^{-1}$ , and shows little dependence on the uplink bandwidth; this shows that, at wide duplex separations, the noise floor is dominated by thermal noise. However, for the narrow duplex separation the Tx noise PSD is highly dependent on the uplink bandwidth, with the 20 MHz uplink bandwidth resulting in a  $>23 \text{ dB}$  increase in Tx noise PSD compared to the 5 MHz uplink bandwidth, this being due to PA spectral regrowth.

Fig. 6 shows the theoretical desensitized antenna referred noise figure as a function of Tx-Rx isolation calculated using the measured values for Tx noise PSD, thereby quantifying desensitization and isolation requirements for LTE UE devices. For the narrow duplex separation with 5 MHz bandwidth, and all configurations with wide duplex separations, 45 dB isolation is sufficient to achieve an 6-7 dB NF, which may be acceptable for cellular applications. However for the 10 MHz and 20 MHz uplink bandwidths with narrow duplex separation, the isolation requirements are much higher. For 20 MHz uplink bandwidth, some 65-70 dB would be required to achieve an acceptable NF; the same is also true for the ultra-narrow 20 MHz duplex separation.



#### IV. LTE THROUGHPUT SIMULATIONS

LTE throughput simulations were used to assess the impact of isolation on sensitivity in LTE UEs [7]. The MATLAB LTE system toolbox was used to simulate a 20 MHz LTE downlink channel subject to receiver thermal noise and desensitization from Tx noise. Receiver thermal noise and desensitization noise are both modeled as white Gaussian noise. Signal and noise powers are calculated according to the model presented in section II (see Fig. 3). The noise power is calculated according to the three noise PSD values measured for the 55 MHz duplex separation (see Section III). The antenna port receive power is -94 dBm (the reference sensitivity for 20 MHz downlink bandwidths for unrelaxed sensitivity testcases [7]). The downlink channel parameters are those specified for 20-MHz LTE downlink sensitivity test cases (100 LTE resource blocks, orthogonal frequency division multiplexing QPSK signaling, code rate 1/3, static frequency flat radio channel [7]). The simulated throughput is calculated as the Tx-Rx isolation is varied from 30-70 dB.

Fig. 7 plots the simulated throughput against Tx-Rx isolation. Results show that, between simulations with different uplink bandwidths, there is a large difference in the level of isolation required to achieve -94 dBm Rx sensitivity. Only 41.7 dB isolation is required to achieve >95% throughput (as required to pass the test [7]) with a 5 MHz uplink bandwidth, increasing to 48.6 dB for a 10 MHz uplink bandwidth, and very high Tx-Rx isolation of 65.0 dB is required for the 20 MHz uplink bandwidth. The current state-of-the-art in acoustic duplexers have been designed to cope with this corner case of maximum Tx power, maximum Tx bandwidth, and narrow separation, however, it is pertinent to note that *the LTE sensitivity specification does not always require this type of configuration to be tested*. For LTE band 28, the 20 MHz downlink sensitivity testcase specifies an uplink bandwidth of only 5 MHz, occupying the upper 5 MHz of the 20 MHz uplink band (an effective duplex separation of 47.5 MHz) thereby reducing the Tx noise and relaxing the isolation requirement [7, Section 7.3]. Using the measurement setup described in Section III, the Tx noise PSD at the Rx frequency was measured as -129.9 dBm Hz<sup>-1</sup> for this bandwidth/separation configuration. Furthermore, for band 28 with 20 MHz downlink bandwidth, the testcase is further relaxed by increasing the receiver sensitivity power requirement to -91 dBm (additional relaxations are applied in carrier aggregation (CA) scenarios according to the *maximum sensitivity degradation* parameter, however CA is not considered in this paper). To determine the minimum isolation requirement for this LTE sensitivity testcase, the throughput simulation was also run using these parameters, and the results (see Fig. 7) show that only 37.8 dB Tx-Rx isolation is required to meet this sensitivity specification. Thus, although duplexers with reduced Rx band isolation would result in performance degradation for some bandwidths/duplex separations as compared to SAW duplexers, such devices could still comply with the specification; designers of future mobile handsets may choose to trade receiver sensitivity for tunability.

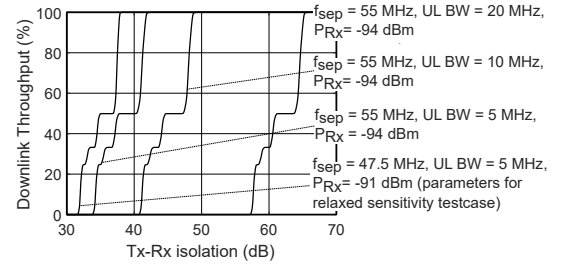


Fig. 7. Simulated downlink throughput as a function of Rx band Tx-Rx isolation for different Tx bandwidths, duplex separations, and Rx powers.

#### V. CONCLUSIONS

Tunable duplexer designs, such as the electrical balance duplexer, may provide lower isolation compared to SAW duplexers, but can be tuned over wide frequency ranges to cover a large number of bands. This paper has investigated the impact of reduced Tx-Rx isolation, and quantified minimum isolation requirements for LTE user equipment. The Rx NF has been calculated as a function of Tx noise at the Rx frequency, and the theoretical analysis has been parametrized using measurements of the Tx noise produced by an LTE handset PA, showing that reducing the isolation can have a severe detrimental impact on the Rx NF for configurations with narrow duplex separations and wide uplink bandwidths.

LTE downlink throughput simulations have demonstrated that high isolation (e.g. 65-70 dB) is needed to avoid Rx desensitization in configurations with wide uplink bandwidths and narrow duplex separations. However, the analysis presented herein shows that this level of isolation is not necessarily required in order to pass LTE sensitivity testcases. For the specific example of LTE band 28, as given above, only ~38 dB of Tx-Rx isolation in the Rx band was required for UE Rx sensitivity specification compliance.

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